Arnold Schwarzenegger
Governor

COMPARISON OF FIFTY-SEVEN YEAR CALIFORNIA REANALYSIS DOWNSCALING AT 10 KILOMETERS (CaRD10) WITH NORTH AMERICAN REGIONAL REANALYSIS

PIER PROJECT REPORT

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Acknowledgments

Preface

The Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The PIER Program, managed by the California Energy Commission (Energy Commission), annually awards up to $62 million to conduct the most promising public interest energy research by partnering with Research, Development, and Demonstration (RD&D) organizations, including individuals, businesses, utilities, and public or private research institutions.

PIER funding efforts are focused on the following RD&D program areas:

- Buildings End-Use Energy Efficiency
- Energy-Related Environmental Research
- Energy Systems Integration
- Environmentally Preferred Advanced Generation
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy Technologies

The California Climate Change Center (CCCC) is sponsored by the PIER program and coordinated by its Energy-Related Environmental Research area. The Center is managed by the California Energy Commission, Scripps Institution of Oceanography at the University of California at San Diego, and the University of California at Berkeley. The Scripps Institution of Oceanography conducts and administers research on climate change detection, analysis, and modeling; and the University of California at Berkeley conducts and administers research on economic analyses and policy issues. The Center also supports the Global Climate Change Grant Program, which offers competitive solicitations for climate research.

The California Climate Change Center Report Series details ongoing Center-sponsored research. As interim project results, the information contained in these reports may change; authors should be contacted for the most recent project results. By providing ready access to this timely research, the Center seeks to inform the public and expand dissemination of climate change information; thereby leveraging collaborative efforts and increasing the benefits of this research to California's citizens, environment, and economy.

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For more information on the PIER Program, please visit the Energy Commission's website www.energy.ca.gov/pier/ or contract the Energy Commission at (916) 654-5164.

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Abstract

The National Center for Environmental Prediction (NCEP)/National Center for Atmospheric Research (NCAR) Reanalysis for the period 1948–2005 was dynamically downscaled to hourly, 10 kilometer (km) resolution over California using the Regional Spectral Model. The CaRD10 was compared with the North American Regional Reanalysis (NARR), which is a data assimilation regional analysis at 32 km resolution and three-hourly output with the Eta model for the period 1979–present, using the NCEP/DOE Reanalysis as lateral boundary conditions. The large-scale component of atmospheric analysis is practically the same in CaRD10 and NARR. The CaRD10 near-surface temperature and winds on monthly and hourly scales are similar to NARR, with more regional details available in CaRD10. The Southwestern monsoon is poorly reproduced in CaRD10, due to the position of the lateral boundary. The spatial pattern of the two precipitation analyses is similar, but CaRD10 shows smaller-scale features despite a positive bias. The trend of 500 hectopascal (hPa) height is similar in the two analyses, but the near-surface temperature trend does not agree, suggesting the importance of regional topography, model physics, and land surface schemes. In both analyses, precipitation shows a positive trend in areas with large precipitation and a decreasing trend on the leeward side of the Sierra. Several synoptic examples such as the Catalina Eddy, Coastally Trapped Wind Reversal, and Santa Ana winds are better produced in the CaRD10 than in the NARR, suggesting that the horizontal resolution of the model has a large influence on these small-scale events. A comparison of a major storm event shows that both analyses suffer from large budget residual. CaRD10's large precipitation is related to wind direction, spatial distribution of precipitable water, and a large moisture convergence. As far as the two regional reanalyses are concerned, uncertainties are large. Overall, CaRD10 shows a very good agreement with the NARR and benefits from higher spatial resolution and fine-scale topography. Dynamical downscaling forced by a global analysis is a computationally economical approach to regional scale long-term climate analysis and can provide a high quality climate analysis comparable to data assimilated regional reanalysis.

Keywords: Reanalysis downscaling, CaRD10, regional climate modeling, Regional Spectral Model, North American Regional Reanalysis, NARR, NCEP, NCAR

Executive Summary

Introduction

In an earlier project, this report's authors dynamically downscaled the National Center for Environmental Prediction (NCEP) and National Center for Atmospheric Research (NCAR) Reanalysis for the period 1948–2005 to hourly, 10 kilometer (km) resolution over California, nearby states, and the Pacific Ocean using the Regional Spectral Model.

The resulting Public Interest Energy Research (PIER) project report, *Fifty-seven Year California Reanalysis Downscaling at 10 Kilometers (CaRD10)*, presented the comprehensive validation of this reanalysis downscaling against station observations, Higgins-gridded precipitation analysis, and Precipitation-elevation Regression on Independent Slopes Model (PRISM) precipitation analysis. It was found that the downscaled near-surface wind, temperature, and precipitation fit much better with regional-scale station observations than with the NCEP/NCAR Reanalysis used to force the regional model—supporting the premise that the regional downscaling is a viable method to attain regional detail from large-scale analysis without regional data assimilation.

In a separate project, the National Center for Environmental Prediction conducted a high-resolution regional reanalysis—the North American Regional Reanalysis (NARR)—over the continental United States. This was a comprehensive effort to produce historical high-resolution analysis over the continental United States using a state-of-the-art variational data assimilation system utilizing various types of high-spatial-resolution satellite observation, as well as gridded observed precipitation.

The study's authors felt that it would benefit dataset users to examine how the differences between these two systems affect the resultant analyses for use in synoptic and climate studies.

Purpose

The purpose of this project was to produce datasets for regional-scale global change research and application.

Project Objectives

This project's objective was to conduct an in-depth comparison of CaRD10 and NARR at various time scales and to weigh the pros and cons of the regional reanalyses and their uncertainties.

Project Outcomes

The NCEP/ NCAR Reanalysis for the period 1948–2005 was dynamically downscaled to hourly, 10 kilometer (km) resolution over California using the Regional Spectral Model. The CaRD10 was compared with the North American Regional Reanalysis (NARR), which is a data assimilation regional analysis at 32 km resolution and three-hourly output with the Eta model for the period 1979–present, using the NCEP/DOE Reanalysis as lateral boundary conditions.

Conclusions

The large-scale component of atmospheric analysis is practically the same in CaRD10 and NARR. The CaRD10 near-surface temperature and winds on monthly and hourly scales are similar to NARR, with more regional details available in CaRD10. The Southwestern monsoon is poorly reproduced in CaRD10, due to the position of the lateral boundary. The spatial pattern of the two precipitation analyses is similar, but CaRD10 shows smaller-scale features despite a positive bias. The trend of 500 hectopascal (hPa) height is similar in the two analyses, but the near-surface temperature trend does not agree, suggesting the importance of regional topography, model physics, and land surface schemes. In both analyses, precipitation shows a positive trend in areas with large precipitation and a decreasing trend on the leeward side of the Sierra. Several synoptic examples such as the Catalina Eddy, Coastally Trapped Wind Reversal, and Santa Ana winds are better produced in the CaRD10 than in the NARR, suggesting that the horizontal resolution of the model has a large influence on these small-scale events. A comparison of a major storm event shows that both analyses suffer from large budget residual. CaRD10's large precipitation is related to wind direction, spatial distribution of precipitable water, and a large moisture convergence. As far as the two regional reanalyses are concerned, uncertainties are large. Overall, CaRD10 shows a very good agreement with the NARR and benefits from higher spatial resolution and fine-scale topography. Dynamical downscaling forced by a global analysis is a computationally economical approach to regional scale long-term climate analysis and can provide a high quality climate analysis comparable to data assimilated regional reanalysis.

Recommendations

The study demonstrates the quality of CaRD10 by comparison with a regional data assimilation reanalysis. The authors encourage that CaRD10 be used for regional-scale global change research and application in California. The users of CaRD10 are recommended to fully understand the pros and cons of CaRD10 that are described in the study.

Benefits for California

CaRD10 provides a high quality datasets for regional-scale global change research and application in California. The study demonstrated that CaRD10 is comparable and often superior to a regional data assimilation reanalysis. California can benefit from CaRD10's very high spatial resolution (10 kilometers) and high temporal resolution (hourly) datasets of regional climate.

1.0   Introduction

For the purpose of producing datasets for regional-scale global change research and application, the National Center for Environmental Prediction (NCEP) and National Center for Atmospheric Research (NCAR) Reanalysis (Kalnay et al. 1996) for the period 1948–2005 was dynamically downscaled to hourly, 10 kilometer (km) resolution over California, nearby states, and the Pacific Ocean using the Regional Spectral Model. The Public Interest Energy Research (PIER) project report, *Fifty-seven Year California Reanalysis Downscaling at 10 Kilometers (CaRD10)* (Kanamitsu and Kanamaru 2006) presented the comprehensive validation of this California Reanalysis Downscaling at 10 km (CaRD10) analysis against station observations, Higgins-gridded precipitation analysis (Higgins et al. 2000), and Precipitation-elevation Regression on Independent Slopes Model (PRISM, Daly et al. 1994, 2001, 2002) precipitation analysis. It was found that the downscaled near-surface wind, temperature, and precipitation fit much better with regional-scale station observations than with the NCEP/NCAR Reanalysis used to force the regional model—supporting the premise that the regional downscaling is a viable method to attain regional detail from large-scale analysis without regional data assimilation. This ability of the downscaling was found on all time scales, ranging from hourly to decadal, or from diurnal variation to multi-decadal trend. However, the downscaled analysis is not free from problems. Particularly, it suffers from positive precipitation bias for heavy precipitation events. The CaRD10 analysis is also inaccurate near the lateral boundary where regional detail is damped by the lateral boundary relaxation towards the coarse-resolution global Reanalysis.

There are several long-term climate reanalysis datasets available that have been widely used in the climate research community. NCEP and NCAR have been producing a global reanalysis dataset (hereafter referred to as *R1*) that starts in 1948 and continues to the present in near real time. An updated version of R1 is the NCEP and Department of Energy Reanalysis (NCEP/DOE Reanalysis, Kanamitsu et al. 2002, hereafter referred to as *R2*), which starts from 1979 and continues to the present. Other global reanalyses are available from: the European Centre for Medium-Range Weather Forecasts (ECMWF), that covers the period of 1979 to the mid 1990s (ERA15, Gibson et al. 1997) and mid-1957 to 2001 (ERA40, Simmons and Gibson 2000; Uppala et al. 2005); from the National Aeronautic and Space Administration's (NASA's) Data Assimilation Office (DAO) (Schubert et al. 1995), and from the Japan Meteorological Agency (JRA-25, www.jreap.org/indexe.html). A number of intercomparison studies of global reanalyses have been published comparing various aspects of analysis; storm tracks (Hodges et al. 2003; Trigo 2006), water budgets in the Western United States (Leung et al. 2003), Southern Hemisphere circulation (Bromwich and Fogt 2004), rainfall in the U.S. Great Plains (Ruiz-Barradas and Nigam 2005), surface air temperature (Simmons et al. 2004), pressure field, sea surface temperature, and latent heat flux (Sterl 2004), and atmospheric energy budgets (Trenberth et al. 2002), among others. Uppala et al. (2005) provides an overview of ERA-40's comparison against R1. These global reanalyses originate from a similar set of observations, yet often produce different climate analyses, due to differences in the assimilation systems. Although long-term R1 and ERA-40 analyses are advantageous for climate research, the coarse resolution of these analyses is

not quite suited for use in regional studies and for comparison with a regional-scale analysis such as CaRD10.

Recently, NCEP conducted a high-resolution regional reanalysis over the continental United States (North American Regional Reanalysis (NARR), Mesinger et al. 2006). NARR is a comprehensive effort to produce historical high-resolution analysis over the continental United States using a state-of-the-art variational data assimilation system utilizing various types of high-spatial-resolution satellite observation, as well as gridded observed precipitation. NARR was performed with the horizontal resolution of 32 km and three hourly outputs for the period of 1979 to present.

When the CaRD10 project was first designed, the major objective was to produce a long-term, high-resolution climate dataset over California, but in order to avoid a duplicate effort with NARR the study team tried to produce products that NARR may not be able to provide. The choices of 10 km resolution, hourly output, and coverage of 1948 to present are the three major features that distinguish CaRD10 from NARR. On the other hand, CaRD10 does not cover the large area that NARR covers, and furthermore, it does not use any regional-scale observations, whereas NARR is based on full regional variational data assimilation. It is the interest of this study's authors (as well as dataset users) to examine how these system differences affect the resultant analyses for use in synoptic and climate studies.

The first PIER project report on CaRD10 (Kanamitsu and Kanamaru 2006) discussed a station-based comparison of temperature and wind between CaRD10 and NARR. The 10 km resolution in CaRD10 made the wind and temperature analysis over land fit better with observations than NARR on daily and monthly time scales. This suggests that resolving detailed topography is very important for regional analysis, and gives advantage to CaRD10 over California where complex topography dominates.

Encouraged by these results, the research team decided to make an in-depth comparison of CaRD10 and NARR at various time scales and to weigh the pros and cons of the regional reanalyses and their uncertainties. The comparison of CaRD10 and NARR is not exactly analogous to the comparison of two global reanalyses because of the large differences in these two analysis systems. CaRD10 is a downscaled analysis of R1 without direct observation input. NARR is a regional reanalysis with assimilation of observations, with R2 as a lateral boundary condition. There are several major differences in the observations used between R1 (large-scale forcing for CaRD10) and NARR. For example, R1 uses satellite-retrieved temperature, but NARR uses raw radiance observation and more surface observations. When CaRD10 is compared with NARR, however, the large-scale components of the two analyses are not expected to be very different (this will be discussed in Section 2). The major difference should appear in the regional scale, since NARR uses a dense surface observation network. It is, however, noted that the NARR does not use two-meter temperature observation over land. It is also noted that although near surface winds and humidity are used, their impact on the analysis is found to be "marginal" (Mesinger et al. 2006). Thus, the only small-scale observation that affected NARR was the surface pressure, but how much the small-scale surface pressure observations affect the analysis of other variables is not very clear. Accordingly, the dense surface observations in NARR may not contribute significantly

to their resulting analysis. In addition to conventional surface observations, NARR uses observed gridded precipitation in the data assimilation. The observed precipitation adds small-scale features to the resulting analysis. This distinguishes NARR from other global reanalyses and makes it a very unique product.

The dynamical downscaling technique used in CaRD10 is less accurate than the data assimilation analysis, since it does not use regional small-scale observations. However, as was shown in the comparison of the analyses with station observations in the first PIER Project Report on CaRD10 (Kanamitsu and Kanamaru 2006), the CaRD10 is not necessarily worse than NARR, which is probably due to its finer horizontal resolution and the use of Scale Selective Bias Correction (SSBC, Kanamaru and Kanamitsu 2005; Kanamaru and Kanamitsu 2006). The SSBC reduces the large-scale error that develops within the regional domain, and simulates the data assimilation of large-scale analysis via the nudging process. Because the fit of the analysis to station observations varies considerably between CaRD10 and NARR (Kanamitsu and Kanamaru 2006), the comparison of CaRD10 and NARR without reference to observation is a demonstration of how these two analyses are similar and/or different, and does not provide the quality of the analysis, with the exception of precipitation (NARR used observed precipitation analysis). In other words, this report more or less examines uncertainties in regional analyses, as the comparison of two independent global reanalyses provides uncertainties in the global reanalyses.

First, it is essential to understand the difference in surface topography between CaRD10 and NARR, which is probably one of the greatest factors accounting for the difference in surface variables. Figure 1 shows the surface height difference between CaRD10 and NARR. The largest difference is in the Sierra Nevada, where CaRD10 is higher than NARR by as much as 800 meters (m) and lower by up to 600 m on the leeward side of the mountain ranges. The difference is due to the orography smoothing in each model on different horizontal spatial resolutions (10 km for CaRD10, and 32 km for NARR). The surface height difference inevitably causes differences in variables such as temperature and precipitation, where the height difference is large. Readers are advised to refer to this figure when comparing the difference of the two analyses studied in this report.

The report is organized as follows. Section 2 compares the large-scale analyses between CaRD10 and NARR. Section 3 compares the trends of near-surface temperature, 500 hectopascal (hPa) height, and precipitation. Section 4 presents comparisons of several synoptic scale events. Section 5 focuses on a major storm event and compares the water budgets. Section 6 concludes the report. Monthly mean comparisons of near surface temperature, surface winds, precipitation, soil moisture, and latent heat flux were discussed in the first PIER project report on CaRD10 (Kanamitsu and Kanamaru 2006). Also presented in that report was hourly scale comparison of surface winds. They are not repeated in this report, but summarized in Section 6.
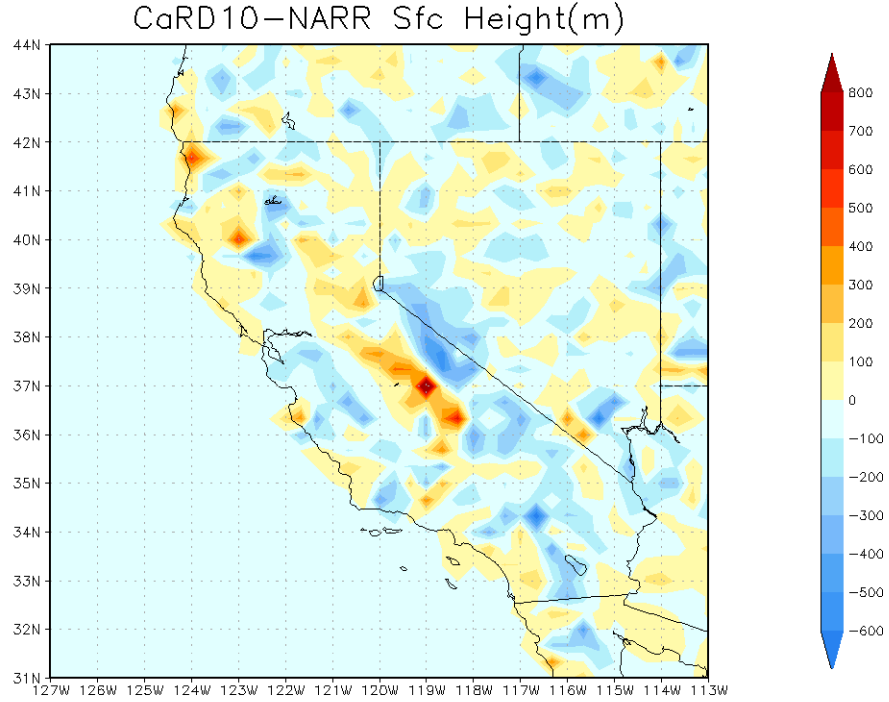
Figure 1. Surface height difference (m) between CaRD10 and NARR

2.0   Difference in Large-scale Analysis

Before comparing CaRD10 and NARR regional-scale analyses for different time scales, this section will first examine the difference in the large-scale component of the two analyses. The difference can be significant, since the observations used in these two analyses are very different—particularly the satellite observations. Examination of the difference is important since CaRD10 is simply forced by large-scale analysis. Therefore, if the large-scale analyses between CaRD10 and NARR are very different, CaRD10 can never be expected to be similar to NARR.

For this comparison, the research team used 500-hPa height fields as a large-scale analysis, because small-scale features appearing near the surface are sufficiently damped, and only large-scale features remain at this level.

The root mean square difference (RMSD) of daily 500-hPa analyses averaged for winter (DJF) and summer (JJA)[1] of 2001 and 2002 are 8.2 m and 7.0 m respectively, which is about the same magnitude as the observational error of radiosonde (Xu et al. 2000). The maximum difference of winter and summer mean 500-hPa height between CaRD10 and NARR for the period 1979–2002 is about 4 m (not shown). These comparisons clearly indicate that the large-scale analyses between CaRD10 and NARR are practically the same.

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[1] DJF = December, January, February, and JJA = June, July, August

3.0   Trends

3.1.   Near-Surface Temperature

Although the NARR period of 1979 to present is too short to conduct a robust long-term trend analysis, it is still of great interest to compare the trends of CaRD10 and NARR in the last quarter of a century to study the difference in the low frequency part of the analyses. Figure 2a shows the comparison of the DJF near-surface temperature trend from 1979 to 2002.
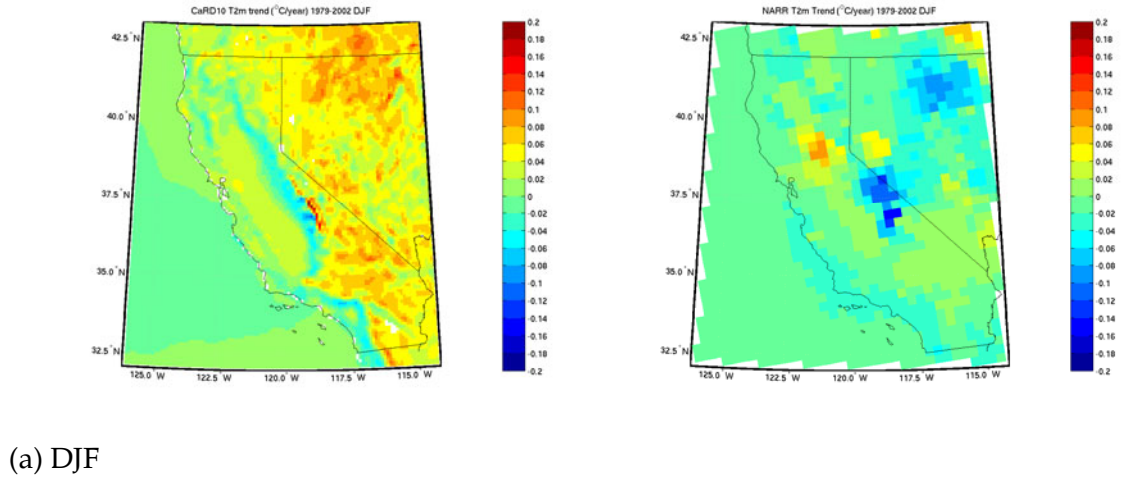
(a) DJF
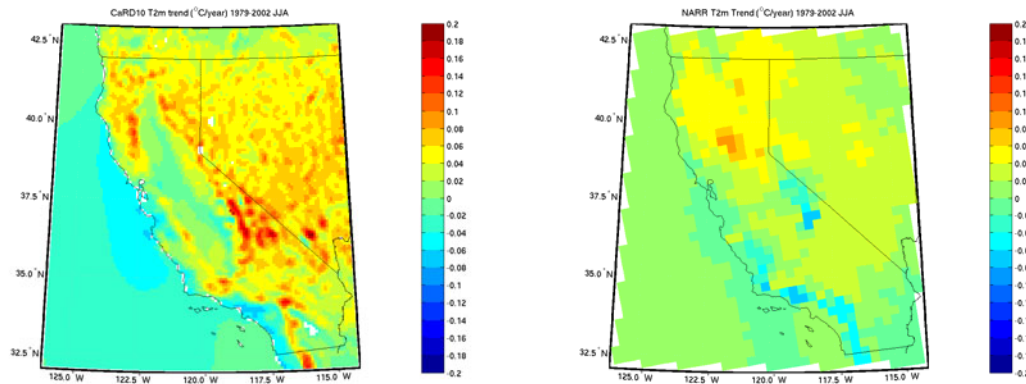
(b) JJA

Figure 2. Comparison of 2 m temperature trend (degrees Kelvin (K)/year) for the period 1979 to 2002 between CaRD10 (left) and NARR (right), in (a) DJF and (b) JJA

Coastal areas and low-elevation valleys do not show a strong trend. CaRD10 produces a negative trend on the windward side of the Sierra Nevada and a positive trend on the leeward side and in most of Nevada. A positive trend is also prevalent for inland

southern California and northern Nevada. NARR shows a positive trend only in the east and the west sides of Lake Tahoe, and it shows a negative trend over the Sierra Nevada and northern Nevada. The rest of the domain shows little trend. Thus, the two analyses are very different in the spatial pattern, except for a negative trend in the windward side of the Sierra and a small negative trend in the coastal areas of southern California. The JJA 2 m temperature trend also shows a negative trend in the southern California coastal areas in both analyses (Figure 2b). The trend is also positive in Northern California in both analyses, but a large positive trend over the northern Central Valley in NARR is replaced by a near zero-trend in CaRD10. The eastern half of the domain shows a positive trend in CaRD10 but only a small positive trend in NARR. In fact the difference between the two analyses in each season is much larger than the difference between two seasons in each analysis. The next subsection will examine the contribution of large-scale analysis to the near-surface temperature trend, for a possible explanation of this dissimilarity between the analyses.
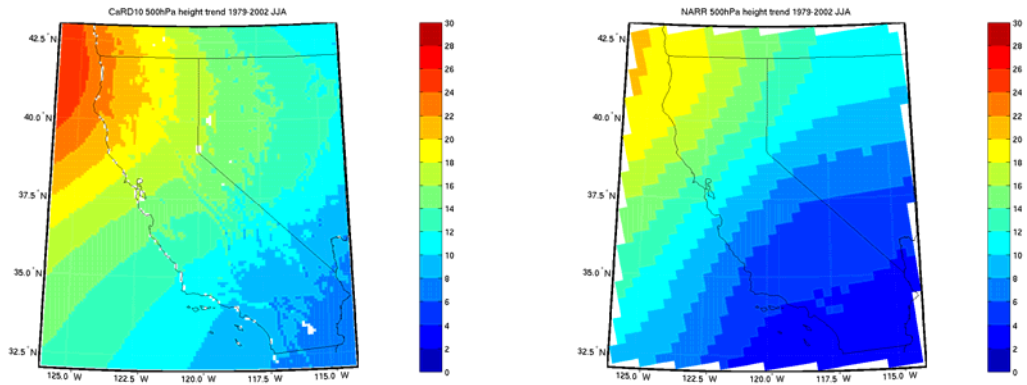
3.2.   500-hPa Height

The trend in 2 m temperature can be partitioned into the trend in large-scale circulation, and the change in local scale. In order to examine the trend in large-scale between the two analyses, this study examined the trend in 500-hPa geopotential height, as was done in Section 2. Figure 3a shows the change in 500-hPa height from 1979 to 2002 from the linearly fitted trend of the height at each grid point. In DJF, there is a gradient of height trend from a negative trend in the northwest corner to a positive trend in the southeast corner in both analyses. In JJA, the entire domain shows a positive trend for both CaRD10 and NARR, but with somewhat different magnitude, and the gradient has been reversed from DJF, but the patterns are again very similar. Thus for both seasons, CaRD10 and NARR show very similar patterns in the 500-hPa height trend, indicating that the trends in the large-scale analysis between the two are similar.

An interesting finding is that the northwest-southeast gradient found in the 500-hPa height trend is not seen in the near-surface temperature trend, thus the trend in large scale (such as the global effect of greenhouse gases) does not seem to be directly correlated to the trend in near-surface temperature. Therefore, the large difference in near-surface trend between the two analyses is due to differences in near surface processes, most likely to land surface conditions and to radiation fluxes reaching the surface. It will be the focus of further research to investigate the cause of the trend near the surface.

The difference in the 500-hPa-height trend between two analyses, although not very large, is examined in some detail below. The difference becomes more apparent when comparing the time series of area-mean root mean square differences (Figure 4). The RMSD between CaRD10 and R1 does not change over time (blue lines). So CaRD10 simply inherits the large-scale trend of R1. This is quite an assuring finding, since it indicates that the trend that appears in R1 is reasonably well maintained in CaRD10. This is a proof that the use of SSBC in CaRD10 is effective in maintaining the low-frequency signal in the lateral forcing.
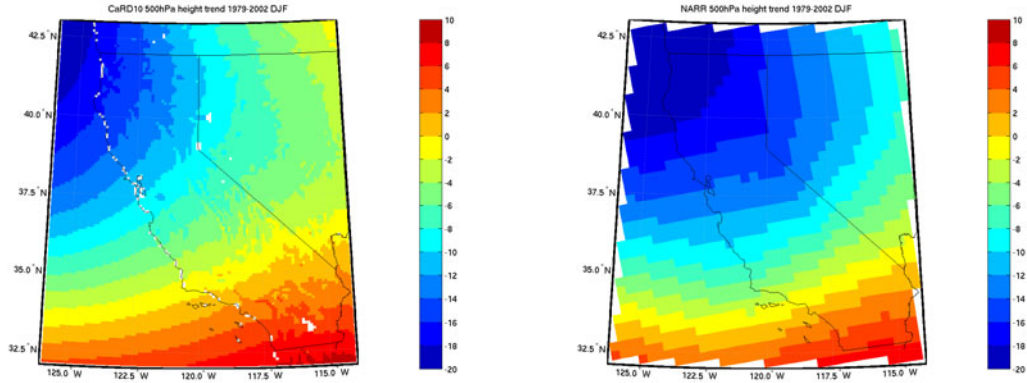
(a) DJF

(b) JJA

Figure 3. Comparison of 500-hPa height trend (m/23years) for the period 1979 to 2002, between CaRD10 (left) and NARR (right), in (a) DJF and (b) JJA

The RMSD between NARR and R2 (used as lateral boundary forcing, green lines) is larger than that between CaRD10 and R1 (blue lines). This is the result of data assimilation without SSBC in NARR. This difference is also much greater than the RMSD between R1 and R2 (magenta lines). The use of raw radiance, additional observations and the use of precipitation in the NARR data assimilation, as well as not using the SSBC, caused these large differences between NARR and R2.

A close examination of Figure 4 shows an apparent decrease in the difference between R1 and R2 with time. In addition, a small decrease in RMSD is also found between R2 and NARR. These two relations (R1 versus R2, and R2 versus NARR) account for the difference between CaRD10 and NARR that decreases even greater with time (black lines). The decrease of the difference between R1 and R2 is probably due to reduced
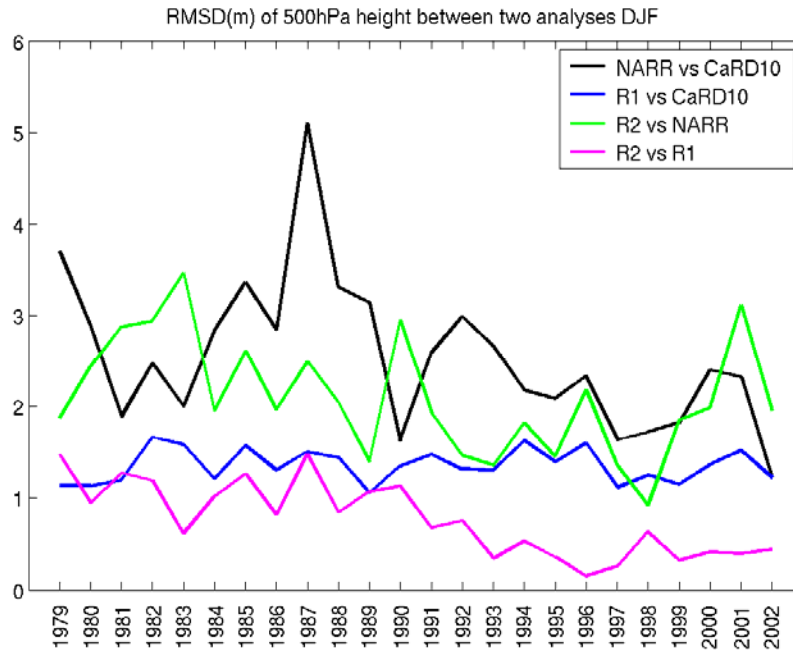
(a)
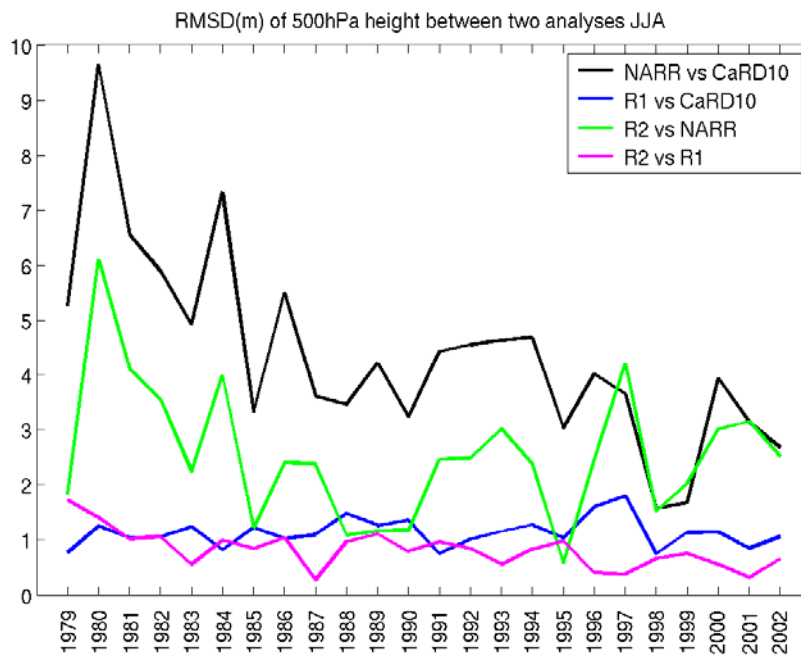
(b)

Figure 4. Time series of area-mean root mean square difference of 500-hPa between two of four analyses (CaRD10, NARR, R1, and R2), in (a) DJF and (b) JJA

uncertainties in the analysis when more data (particularly aircraft data from the Aircraft to Satellite Data Relay system) became more readily available after late 1980. The difference between R1 and R2 is larger over the Pacific, where conventional data coverage is poor (not shown). The greater difference between NARR and R2 in earlier years is considered to be due to the poorer quality of the satellite radiance observation in earlier years. In summary, although the difference in large-scale trends between CaRD10 and NARR is small, changes attributable to uncertainties in analysis and to the different use of satellite observation can still be detected.

3.3. Precipitation

Although 2 m temperature trends show different spatial patterns, the precipitation trend is consistent between the two analyses (Figure 5). DJF precipitation increases in the northwest, where large precipitation is produced in both CaRD10 and NARR. Another common pattern found in both analyses is a precipitation decrease in the leeward side of the Sierra. The rest of the domain with only moderate amounts of precipitation shows little trend. Considering that the CaRD10 precipitation is model-produced, it is quite comforting to find that the low-frequency variability of precipitation is well reproduced, despite the positive bias. This agreement between the two analyses also suggests that the precipitation trend is determined by the trend in large scale, and not by the trend in near-surface fields.
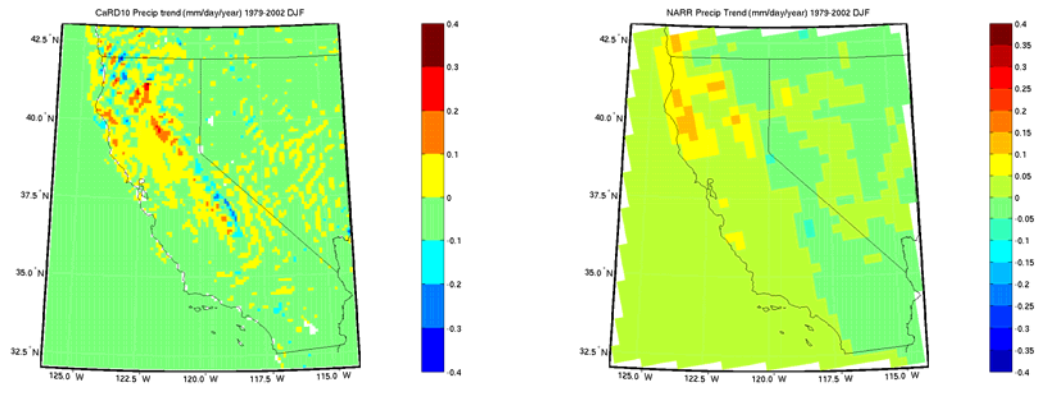
Figure 5. Comparison of precipitation rate trend (m day^{-1} year^{-1}) for the period 1979 to 2002 between CaRD10 (left) and NARR (right), in DJF

4.0 Synoptic Events

4.1. Catalina Eddy

When northerly winds cross the Transverse Ranges and descend over the Santa Catalina Island, the rapid warming of the air mass forms a low-pressure center. This warm low pressure offshore of Santa Barbara and Los Angeles, south of Point Conception, draws marine air along the coast from the south and creates the eddy around the low pressure (Wakimoto 1987; Mass and Albright 1989). CaRD10 is able to produce well-defined

eddies with stronger winds and small-scale structures (Figure 6). Particularly, the 10 km resolution seems to produce cold- and warm-front-like features in the wind direction, and speed that extends from the center of the eddy towards west-southwest and towards southeast, which is an interesting phenomenon for future study. On the contrary, NARR produces a very weak eddy without much small-scale structure. The horizontal resolution is apparently very important for the reproduction of mesoscale eddies, although the detailed analysis and verification require more comparison with observation. The research team has also examined the latest 12 km Eta operational data assimilation analysis for another Catalina Eddy case, and found that the eddy was even weaker (not shown). Therefore, the formation of the eddy in the model may not merely be a function of the horizontal resolution.
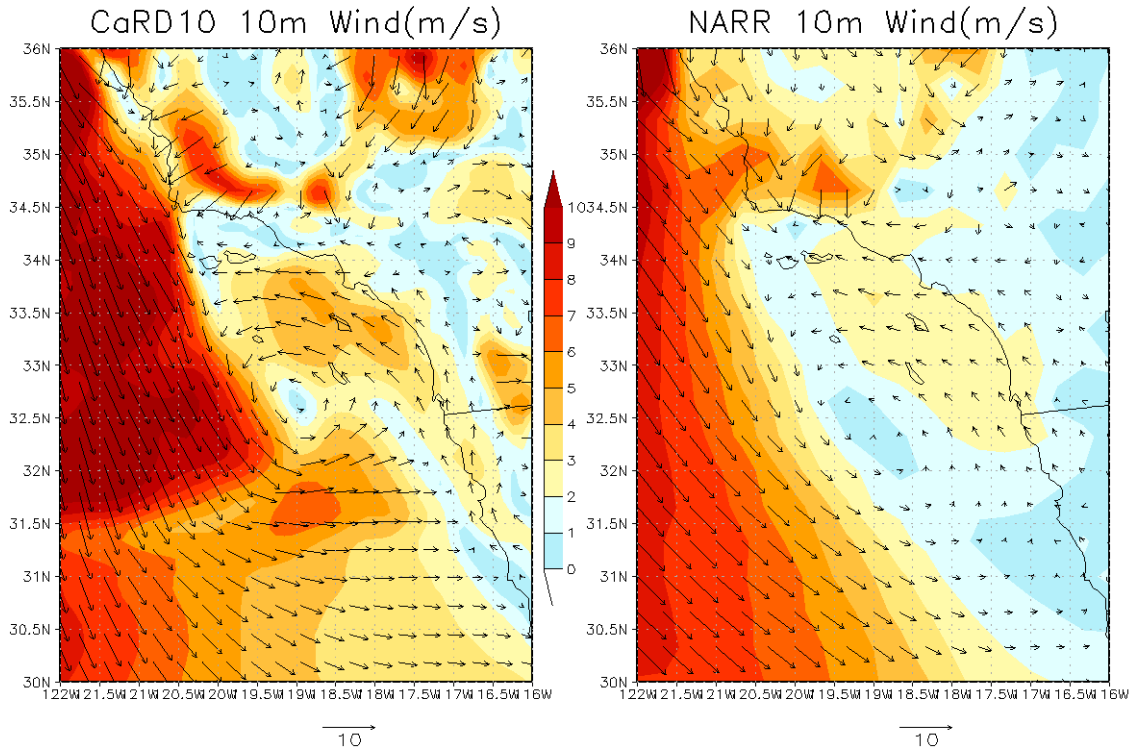
Figure 6. Comparison of a Catalina Eddy event in CaRD10 (left) and NARR (right) at 1500UTC on May 22, 1984. Wind arrows are plotted for only one in three grid cells of CaRD10, to match the NARR resolution. Shades are wind speed (meters per second, m s^{-1}).

4.2.   Coastally Trapped Wind Reversal

When northerly winds along the coastline change direction and head north, this is called Coastally Trapped Wind Reversals (CTWR). These CTWRs typically occur along mountainous coastlines where cold upwelling results in a marine boundary layer capped by a strong inversion (Nuss et al. 2000). Figure 7 shows the evolution of a CTWR event from 18Z on July 21 to 18Z July 22, 1996 as obtained from CaRD10 and NARR. This case was chosen from the Nuss et al. (2000) paper, in which the authors objectively analyzed and predicted streamline from COAMPS (Coupled

Ocean/Atmospheric Mesoscale Prediction System developed at the Fleet Numerical Meteorology and Oceanography Center, their Figure 7). Both CarD10 and NARR show similar streamlines of surface winds at 18Z of July 21 and 00Z of July 22, and agree with Nuss's example. By 18Z on July 22, CTWR is well established in CaRD10, as in the COAMPS forecast, but NARR is not able to produce reversed southerly winds along the coast. Although the evolution of the small-scale flow features between CaRD10 and Nuss's example has differences, the high spatial resolution seems to be important to resolve this regional system.
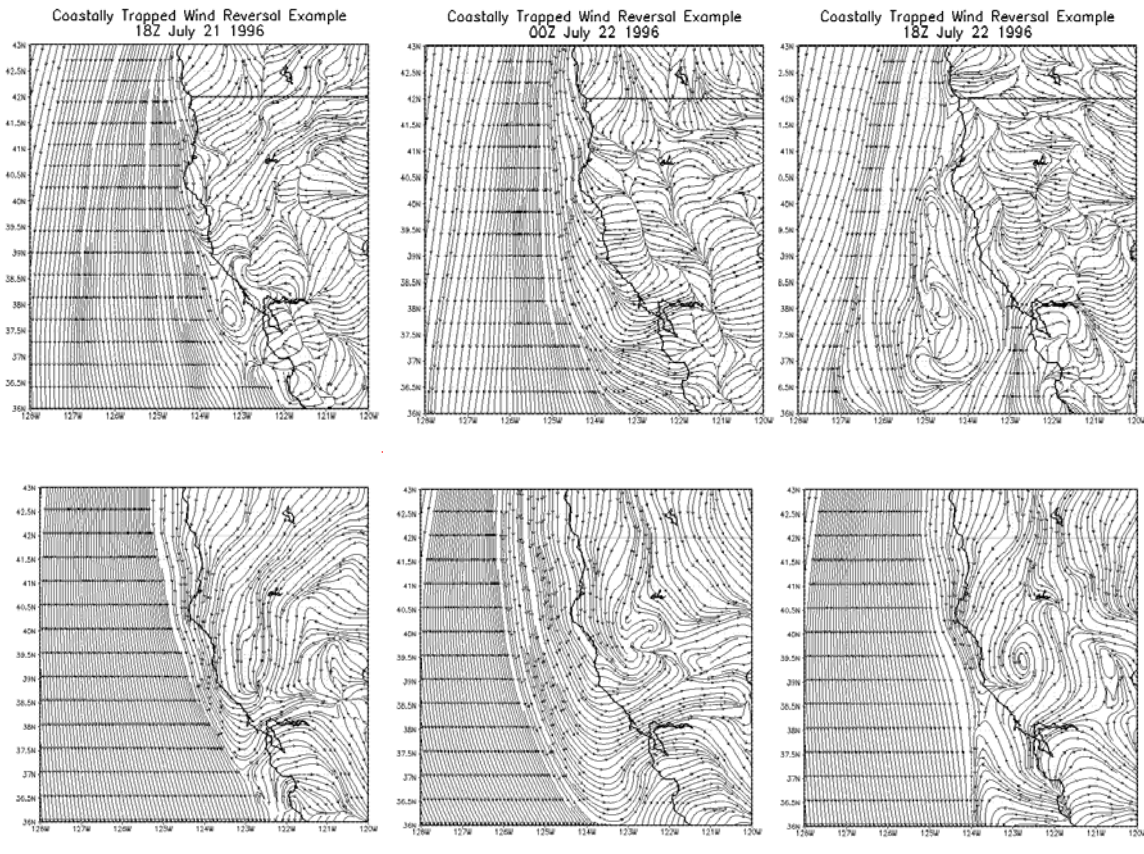
Figure 7. Comparison of the evolution of Coastally Trapped Wind Reversal on July 21 to 22, 1996. Stream lines of 10 m winds are plotted. CaRD10 (top) and NARR (bottom). Left column is 18Z, July 21; middle column is 00Z, July 22; and right column is 18Z, July 22.

4.3.   Santa Ana Winds

When a slow moving high-pressure system intensifies over the northern Midwest during winter, southern California often experiences strong, dry, warm easterly winds blowing from the desert region in eastern California/western Nevada towards the Pacific coast. This is one of the extreme events that define the "weather" in California. Figure 8 shows an example of very strong Santa Ana event at 00Z on October 26, 2003, when many parts of southern California experienced wildfires (Cedar fire; Keely et al. 2004). A 2 m temperature anomaly from each analysis's 00Z October 2003 mean and full-field 10 m winds are plotted. NARR shows only a modest positive temperature

anomaly (up to 4°C) along the coastal areas of southern California, as opposed to 10°C or more in CaRD10, which is more realistic. Both analyses show a similar northerly flow over land, but the winds in CaRD10 are stronger. The two analyses differ in the wind pattern offshore of Los Angeles and San Diego. CaRD10 shows a complex wind response with easterly wind extending more into the ocean area, while NARR shows only consistent northwesterly winds over the same area. Both analyses produce warmer temperature along the northern California/Oregon coastline, due to the anticyclonic circulation centered over the northern Midwest.
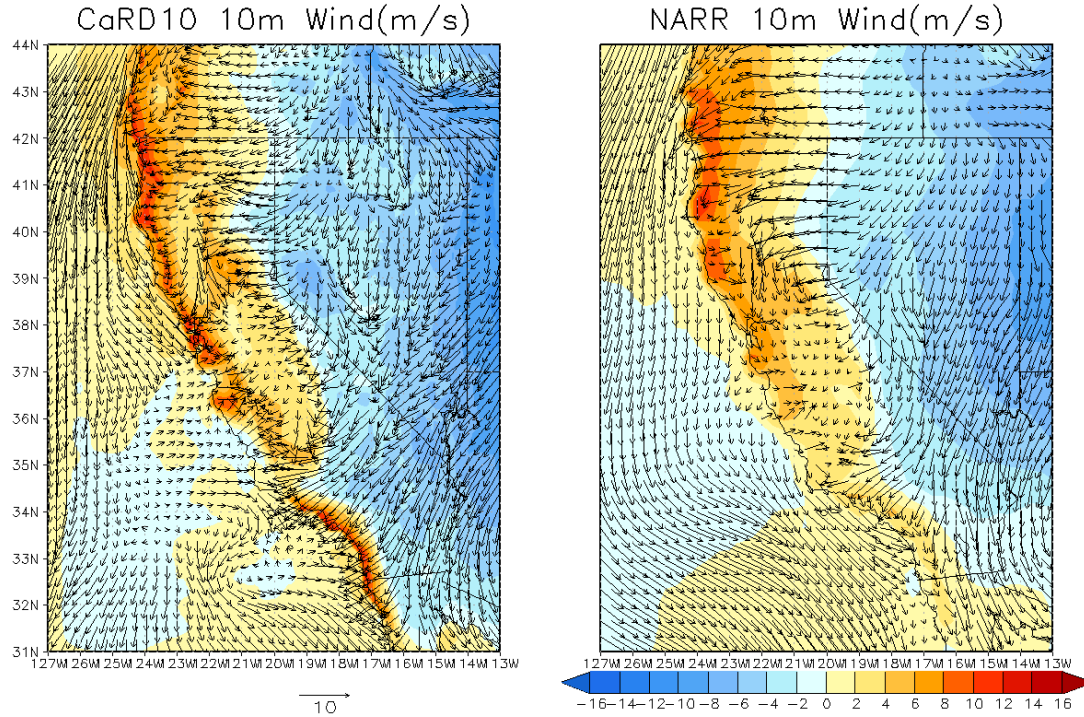
Figure 8. Comparison of a Santa Ana event at 00Z October 26, 2003. Arrows are 10 m wind vectors (m s^{-1}). Shades are temperature anomaly (K) from each analysis's 00Z October, 2003 mean.

In summary, CaRD10's higher resolution seems to produce stronger regional-scale circulation, with more small-scale features. Evaluating the analyses is very difficult, due to the lack of small-scale observation over the ocean. Physical and dynamical analysis of the analyzed circulation is another approach to evaluate CaRD10 and NARR.

5.0   Water Budgets

In order to demonstrate the uncertainties associated with regional reanalyses in a quantitative way, this section presents an example of a water budget study for a major storm event in California, selected from strong atmospheric river events (Ralph et al. 2004). Plots are made for the mean of the three-day event (Nov 7 to 9, 2002). As Table 1 shows, over the whole domain, CaRD10 produces about 15% more area-mean precipitation (11.1 millimeters per day, mm day^{-1}) than NARR (9.7 mm day^{-1}). Spatial

distribution of precipitation is similar in the two analyses, but the intensity of precipitation is different (Figure 9a). Sharp contrast between the area with heavy precipitation and the area with light or no precipitation suggests that the heavier the rain the larger the wet bias becomes in CaRD10. Table 1 shows that the increase in precipitation in CaRD10 from NARR is compensated by a 45% increase in moisture convergence and a 60% increase in evaporation, although the contribution of the moisture convergence is much greater. The change in precipitable water during the three-day event is 1.6 mm day^{-1} for CaRD10 and 1.2 mm day^{-1} for NARR. The budget residual, presented at the right-most column of Table 1 is the result of unmonitored terms in the water budget equation—namely horizontal diffusion and SSBC nudging for CaRD10 and horizontal diffusion and analysis increment (Kanamitsu and Saha 1996) for NARR. These terms are of the same order as the local time change of the precipitable water, and are much larger than evaporation for both CaRD10 and NARR. From a quantitative point of view, since the residual bounds the accuracy of the budget calculations, it is somewhat difficult to conclude, in exact terms, the role of individual terms in the moisture equation. However, the relative importance of individual terms and the comparison of budget between CaRD10 and NARR are still valid from this calculation. Table 1 indicates that for CaRD10, about 83% of the water that converged in the domain fell as precipitation; evaporation accounts for less than 10% of the precipitation; and the remaining water vapor convergence is used to increase the precipitable water in the domain. The increase in precipitable water is *less* than what's available in the atmosphere, thus the model is artificially *taking it away* from the domain via horizontal diffusion and Scale Selective Bias Correction. For NARR, more than 100% of the moisture convergence fell as precipitation, which is compensated by evaporation. The total precipitable water in the domain increases *more* than available, and the analysis system is *adding* more precipitable water to the system via horizontal diffusion and analysis increments. For both analyses, the major term is the moisture convergence and precipitation, indicating simply that the precipitation is controlled by moisture convergence.

Table 1. Area-mean water budget on November 7 to 9, 2002. *CONV* is vertically integrated moisture convergence (mm day^{-1}), *P* is precipitation rate (mm day^{-1}), *E* is evapotranspiration (mm day^{-1}), Δ*PWAT* is precipitable water change from the 1st day to the 3rd day (mm day^{-1}), and *Res* is residual calculated as P-E-CONV+ΔPWAT (mm day^{-1}). Domains are: Whole (Entire domain in Figure 9 (31-45 N and 114-126W)), Area A (heavy precipitation area in the middle of the domain; 35-41N and 118-122W), Area B (northwest corner; 41-45N and 122-126W), and Area C (west of Area A; 35-41N and 122-126W).

Domain	Analyses	CONV	P	E	ΔPWAT	Res
Whole	CaRD10	13.4	11.1	0.9	1.6	-1.7
	NARR	9.4	9.7	0.5	1.2	1.0
A	CaRD10	32.7	30.4	1.5	2.1	-1.8
	NARR	17.7	24.0	0.6	2.1	7.7
B	CaRD10	17.2	16.4	2.3	-3.1	-6.1
	NARR	15.5	21.7	1.5	-2.4	2.3
C	CaRD10	13.0	14.1	0.3	-3.2	-2.4
	NARR	14.0	12.4	0.3	-2.6	-4.4

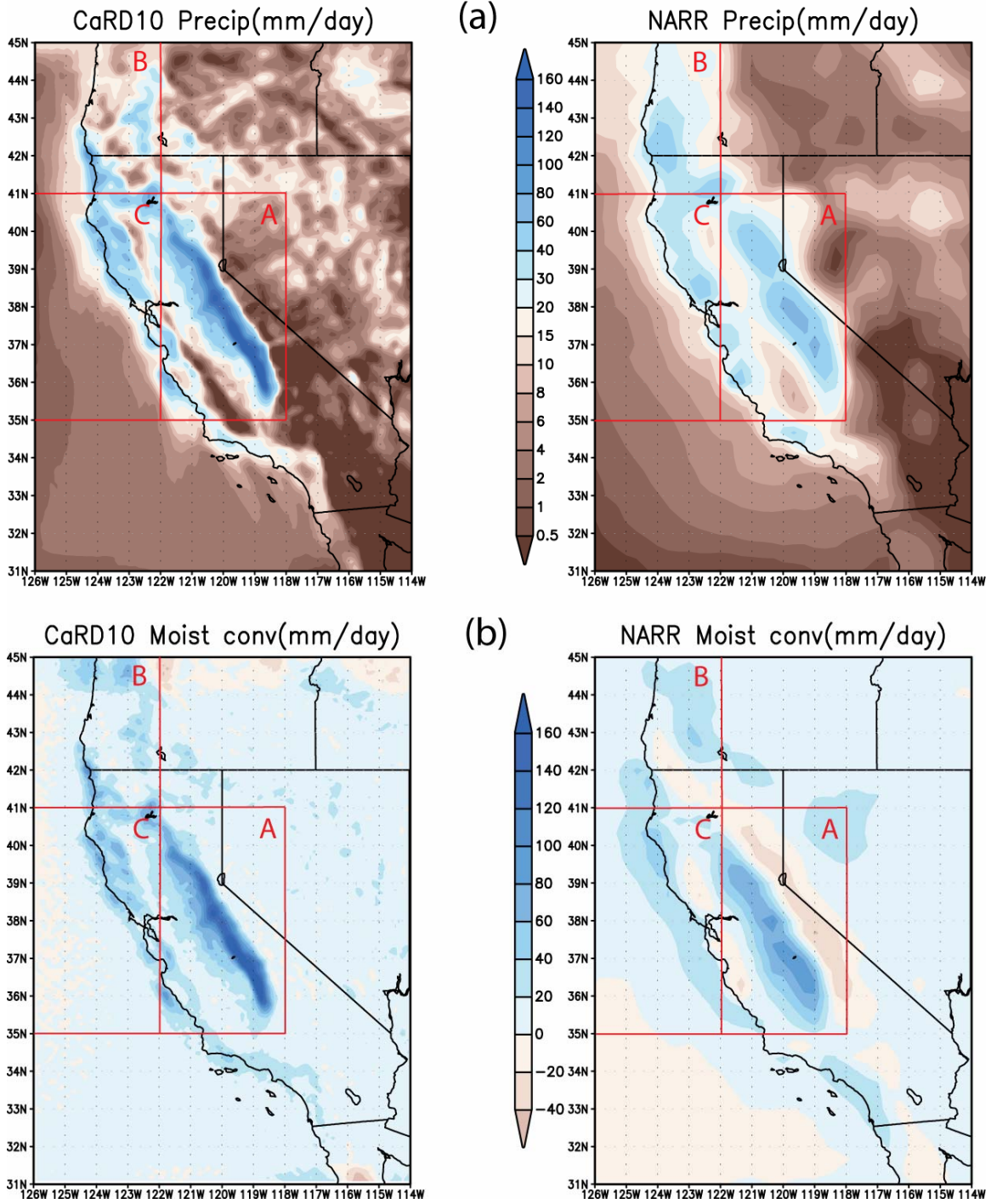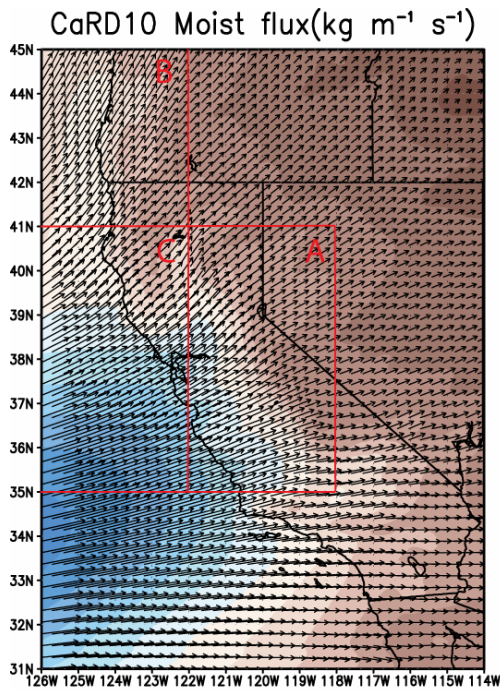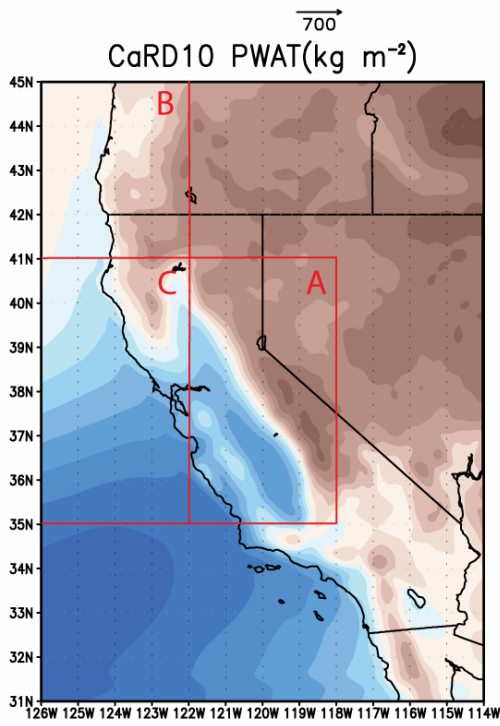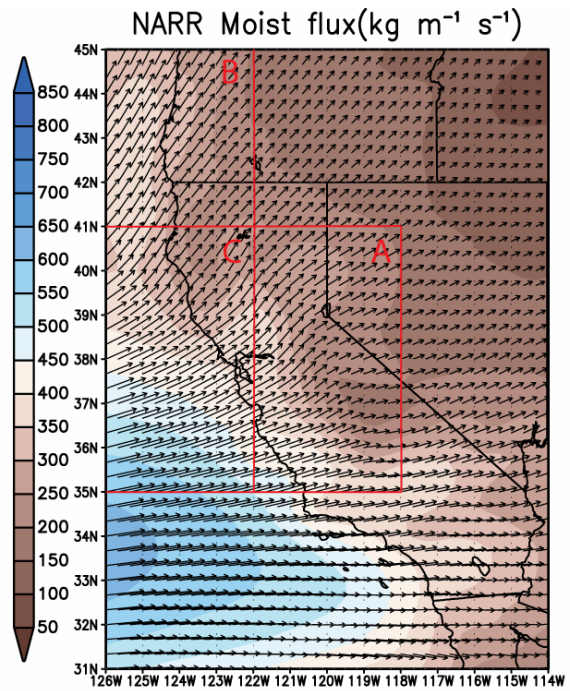**Figure 9. Comparison of a storm event on November 7 to 9, 2002. Left column is CaRD10, and right column is NARR. (a) Precipitation (mm day^{-1}), (b) Moisture convergence (mm day^{-1}), (c) Vertically integrated moisture flux (kg m^{-1} s^{-1}), (d) Precipitable water (kg m^{-2}), and (e) 10 m wind (m s^{-1}). Superimposed are areas A to C for the water budget study.**
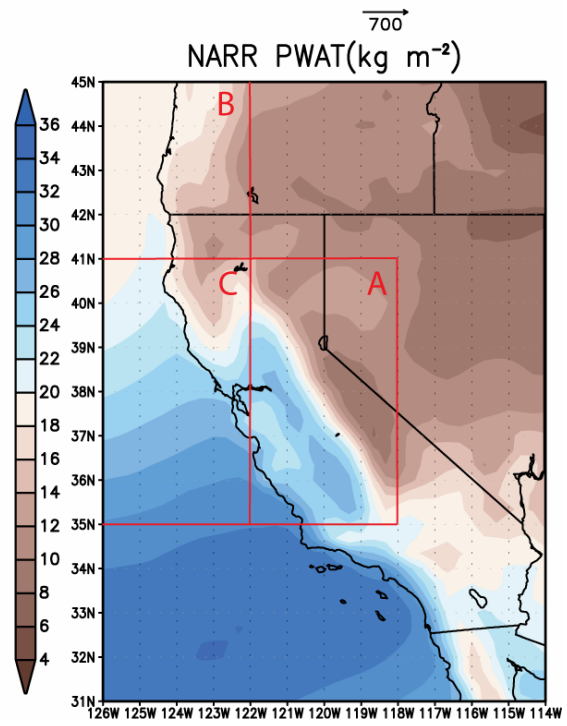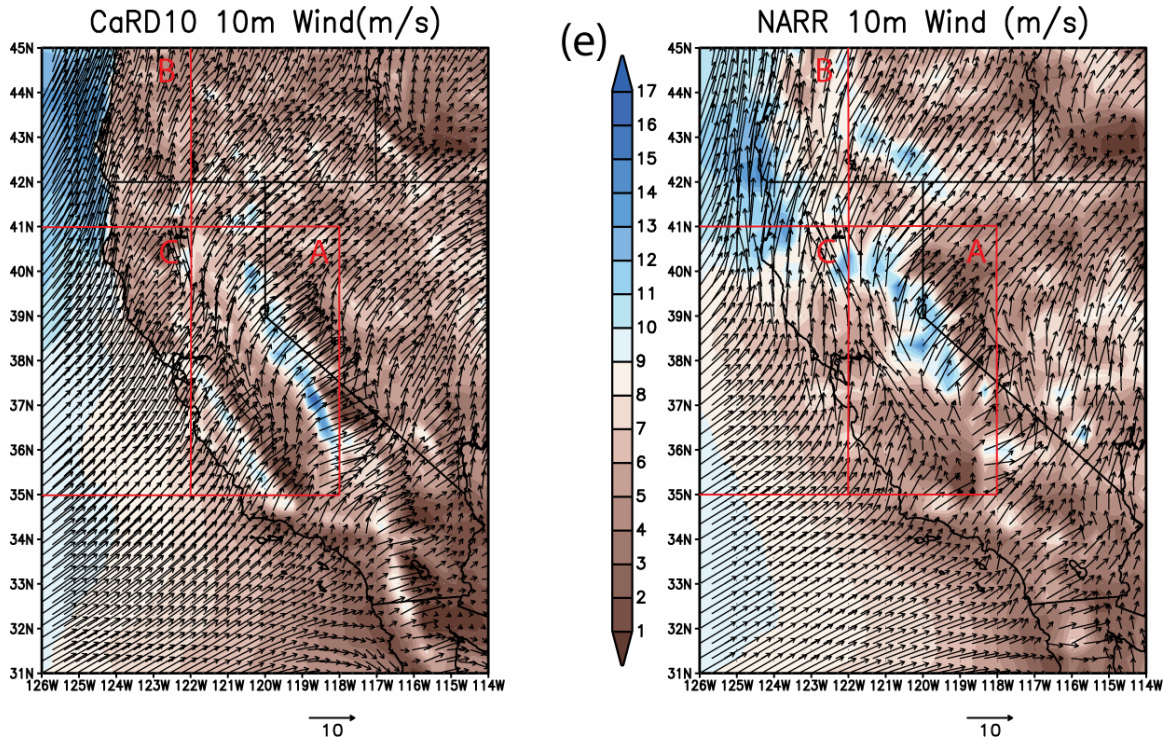
Figure 9. (continued)

Figure 9. (continued)

The research team also separated the water budgets into three areas, by the amount of precipitation found in each area. Area A is the middle of the domain, where most precipitation occurs (35-41N and 118-122W), and CaRD10 produces more precipitation (30.4 mm day^{-1}) than NARR (24.0 mm day^{-1}). Area B is in the northwest corner of the domain, where moderate precipitation is found (41-45N and 122-126W), and CaRD10 has less precipitation (16.4 mm day^{-1}) than NARR (21.7 mm day^{-1}). Area C is the west of the domain A (35-41N and 122-126W) and the precipitation amount is not very different in the two analyses (14.1 mm day^{-1} for CaRD10 and 12.4 mm day^{-1} for NARR). Over Area A, where the precipitation is overestimated by CaRD10, the moisture convergence is much larger than it is in the NARR results.

In other areas with moderate precipitation, the CaRD10 moisture convergence is about the same as that found in the NARR results, suggesting that the moisture convergence is the reason for the overestimation of precipitation in CaRD10, although this study did not determine whether this is the result or the cause. From a more synoptic point of view, although mean precipitable water in Area A is comparable in the two analyses, its spatial pattern shows a large contrast between the moisture-rich windward side and the dry leeward side of the Sierra Nevada in CaRD10 (Figure 9d). This situation suggests that moisture flux dumps a large amount of water when crossing the mountain ranges, which results in large moisture convergence and precipitation.

Another feature of CaRD10 that favors moisture convergence in Area A is the wind pattern (Figure 9e). The 10 m wind comparison suggests that CaRD10 produces a

consistent wind pattern (southwesterly) from the valley that is perpendicular to the mountain ranges. Less southerly wind that escapes without producing orographic precipitation is found in CaRD10 than in NARR. The extra moisture that enters Area A is brought into the domain by a large moisture flux in the southwest corner of the domain (Figure 9c). Slightly larger precipitable water over the ocean accounts for the larger moisture flux in CaRD10 than in NARR. However, the domain average precipitable water is the same in the two analyses. The spatial pattern and gradient of precipitable water, and the direction of winds, make a difference in the water budgets for the storm event between the two analyses.

One curious finding is that the NARR moisture convergence is less than the precipitation for areas A and B, and even the addition of the evaporation cannot fill in the difference. In these areas, the systems require a large artificial moisture source or a decrease in local precipitable water to explain the precipitation, which seems somewhat unrealistic. Whether this is the result of using observed precipitation to force model-dependent variables is an interesting question to be studied.

6.0   Summary and Conclusions

This report compared the dynamically downscaled reanalysis (CaRD10) with the North American Regional Reanalysis. There are several fundamental differences in the basic system design between CaRD10 and NARR. The CaRD10 forces the high-resolution regional model with coarse-resolution global reanalysis without injecting any observations, but uses Scale Selective Bias Correction (SSBC, Kanamaru and Kanamitsu 2006) to maintain the large-scale part of the reanalysis. It ran with 10 km resolution, hourly output from 1948 to present. The NARR is based on the state-of-the-art three-dimensional variational analysis, using surface and high-density satellite raw radiance observations, and also assimilates observed precipitation. The NARR analysis system ran with 32 km resolution, three-hourly output from 1979 to present. The physical processes included in the two models are also different. The purpose of this report is to compare the two analyses, to document the pros and cons of the two products, and to estimate the uncertainties in the high-resolution regional reanalysis for budget study.

The difference in the large-scale analysis is examined from 500-hPa height, to identify possible differences between CaRD10 and NARR due to the use of new and additional datasets in NARR. Monthly averaged daily root mean square difference is on the order of 8 m—the same magnitude as the observational error of radiosonde—confirming that the large-scale analyses between CaRD10 and NARR are very similar.

The first PIER project report on CaRD10 (Kanamitsu and Kanamaru 2006) already presented a few comparisons of CaRD10 and NARR, such as soil moisture and latent heat flux. This section summarizes those findings in conjunction with the results discussed in this report. A comparison of the monthly climatology between the two analyses showed that the CaRD10 near-surface temperature and winds are very similar to NARR, with more regional detail, especially in winter. During the summer, CaRD10 winds associated with the Southwestern monsoon and the Gulf of California low level jet are poor due to the placement of the lateral boundary. CaRD10 has a positive bias in

precipitation compared to NARR, which uses observations, but the spatial pattern of the two are similar and CaRD10 shows small-scale details, especially over the mountains. The comparison of soil moisture revealed that the two analyses are not very similar. This is due to the difference in precipitation (observed in NARR, and model-produced in CaRD10), and to the difference in land process parameterization. The spatial pattern of latent heat flux reflects that of soil moisture, but the two analyses show somewhat more similar patterns than soil moisture.

The diurnal cycle of near-surface temperature is similar in CaRD10 and NARR, but CaRD10 is generally colder. CaRD10 shows spatially detailed patterns of diurnal temperature variation in the Central Valley and the Sierra Nevada. The two surface wind analyses generally agree with each other, but more difference is apparent in nighttime, when winds are generally weak and topography has more influence upon winds. The winds from the San Francisco Bay through the Central Valley and the south of the Sierra into the higher Nevada plains show dissimilarities due to differences in resolving small-scale topography.

The near-surface temperature trends from 1979 to 2002 do not produce consistent spatial patterns between the two analyses. Some common features are a negative trend in the windward side of the Sierra and a small negative trend in the southern California coastal region. In fact, summer and winter show similar trends in each analysis. The large-scale field trend, as represented by 500-hPa geopotential height, is similar in both CaRD10 and NARR. The 500-hPa height trend shows a northwest-southeast gradient in both seasons. Such a spatial pattern is little-seen in the near-surface temperature trend. The surface climate trend seems to be more influenced by regional topography, model physics, and land-surface schemes. The winter precipitation trend is similar in the two analyses. There is a positive trend in the area with large precipitation and a decreasing trend in the leeward side of the Sierra. The rest of the domain shows little trend.

Several synoptic examples are presented to highlight how different topography and spatial resolution affect the local climate. The Catalina Eddy is seen very well in CaRD10 with many mesoscale features, when NARR shows very weak winds. Coastally Trapped Wind Reversal is better simulated in CaRD10, probably because of better representation of mountains along the coast. Santa Ana winds are produced well in both CaRD10 and NARR, but temperature anomaly is much greater in CaRD10 than NARR. For these regional-scale events, the horizontal resolution of the model seems to have a large impact.

In a major three-day storm event, CaRD10 produces more precipitation than NARR in the area mean. Most precipitation-positive bias comes from the mountain areas, where heavy precipitation is observed. The path of precipitable water into southern California is narrower and carries a little more water vapor in CaRD10 than NARR, although the area mean precipitable water is the same. Larger moisture flux due to the precipitable water spatial distribution brings extra moisture over land towards the mountains. The wind direction in CaRD10 is southwesterly and perpendicular to the mountain ranges that favor precipitation. As a result, CaRD10 produces more precipitation than NARR.

The moisture budget calculation showed that both analyses suffer from large budget residual, which is as large as the second-leading term in the moisture equation. These residual terms are the result of horizontal diffusion for both analyses—SSBC for CaRD10, and analysis increment for NARR. In this regard, both analyses have similar quality for a budget study.

Overall, CaRD10 shows a very good agreement with the NARR. In many instances, CaRD10 benefits from higher spatial resolution and fine-scale topography. CaRD10's higher temporal output frequency also aids more detailed diagnostics.

Dynamical downscaling forced by a global analysis is a computationally economical approach to the regional-scale, long-term climate analysis. It can provide a high-quality climate analysis comparable to data assimilated regional reanalysis.

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